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Performance characteristics of part-load operations of a solid oxide fuel cell/gas turbine hybrid system using air-bypass valves

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Abstract

In spite of the high-performance characteristics of a solid oxide fuel cell/gas turbine (SOFC/GT) hybrid system, it is difficult to maintain high-level performance under real application conditions, which generally require part-load operations. The efficiency loss of the SOFC/GT hybrid system under such conditions is closely related to that of the gas turbine. The power generated by the gas turbine in a hybrid system is much less than that generated by the SOFC, but its contribution to the efficiency of the system is important, especially under part-load conditions. Over the entire operating load profile of a hybrid system, the efficiency of the hybrid system can be maximized by increasing the contribution of power coming from the high efficiency component, namely the fuel cell. In this study, part-load control strategies using air-bypass valves are proposed, and their impact on the performance of an SOFC/GT hybrid system is discussed. It is found that air-bypass modes with control of the fuel supply help to overcome the limits of the part-load operation characteristics in air/fuel control modes, such as variable rotational speed control and variable inlet guide vane control.

Keywords: Solid oxide fuel cell; Gas turbine; Hybrid system; Air-bypass mode

1. Introduction

A solid oxide fuel cell (SOFC) is considered to be a potential candidate for the next generation of power devices due to its high efficiency and low emissions. The high-temperature operating characteristics of the SOFC provide hot exhaust gas, which can be used as the heat source for either cogeneration or hybridization with a bottoming cycle. An SOFC/gas turbine (SOFC/GT) system is an example of the hybridization of an SOFC [1]. The role of the gas turbine in an SOFC/GT hybrid system is: (i) to produce additional electrical power with the high-temperature exhaust gas of the SOFC and hence improve system efficiency; (ii) to supply air to the SOFC; (iii) to pressurize the SOFC in the case of a pressurized hybrid system.

Generally, power systems are engineered to be operated under design-point conditions. Under real operating conditions, however, design-point conditions can rarely be maintained due to the varying power (or load) levels that depend on the customer requirements and/or environmental changes. In these situations, it is necessary to operate the system under optimum part-load performance conditions. Here, part-load performance is defined as the performance under conditions that generate less power than under the design-point conditions. Generally, power generation under part-load operating conditions is controlled by adjusting the fuel supply.

The performance characteristics of the SOFC/GT hybrid system under part-load conditions have been studied by many groups [2–4], and it has been concluded that the simultaneous control of air and fuel supplies provides better part-load efficiency than does control of the fuel alone. The gas turbine has an important role in the part-load performance of an SOFC/GT hybrid system due to its rapid reduction of performance at part-load operating conditions, which originates from the characteristics of its components, including the compressor and turbine.

Abbreviations: CAB, cold air-bypass; CABV, cold air-bypass valve; FC, fuel cell, fuel control; FOC, fuel-only control; HAB, hot air-bypass; HABV, hot air-bypass valve; TIT, turbine inlet temperature; VIGV, variable inlet guide vane; VRS, variable rotational speed.

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Nomenclature

A	active area (m^2)
F	Faraday constant (96,485 C mol^{-1})
h	specific enthalpy (kJ kg^{-1})
j	current density (A m^{-2})
LHV	lower heating value (kJ kg^{-1})
$\dot{m}$	mass flow-rate (kg s^{-1})
N	rotational speed (rpm)
P	pressure (Pa or bar)
T	temperature (°C or K)
U_f	fuel utilization factor
V	voltage (V)
$\dot{W}$	power (kW)

Greek letter

η	efficiency

Subscripts

1	compressor inlet
2	compressor exit
3	turbine inlet
4	turbine exit
a	air
b	bypassed air
c	cell
comp	compressor
d	design-point
f	fuel
FC	fuel cell
GT	gas turbine
HS	hybrid system
turb	turbine

In a previous analysis of the part-load performance characteristics of an SOFC/GT hybrid system [5], two kinds of simultaneous air and fuel control modes were considered: (i) variable rotational speed with fuel control, VRS + FC; (ii) variable inlet guide vane with fuel control, VIGV + FC. It was found that both of these modes could provide better efficiency than the fuel-only control (FOC) mode. Furthermore, the VIGV + FC mode could be used as an alternative to the VRS + FC mode, especially in the case of a large power class SOFC/GT hybrid system, which requires a large-class gas turbine operating at a constant speed during part-load operation [4]. Unfortunately, the VIGV + FC mode has a limitation at relatively low power generation. To satisfy the part-load power level under this mode of operation, the amount of air supplied to the system should be controlled by adjusting the angle of the VIGV located in front of the compressor inlet. If the angle of the VIGV is increased above a certain value (e.g., 40°), it causes the compressor to stall and limits the gas turbine operation.

In this study, air-bypass modes are considered as alternatives to the air control of part-load operation of an SOFC/GT hybrid system. The principle of the air-bypass mode is to bypass some of the compressor discharge air using by means of a valve, and to supply it to the turbine inlet stream without passing through the SOFC. This mode reduces the amount of air supplied to the SOFC without changing the amount of air supplied to the compressor. In the present study, the performance of an SOFC/GT hybrid system with two air-bypass modes, i.e., a cold air-bypass (CAB) and a hot air-bypass (HAB), is compared with other cases, and some strategies for the improved part-load performance of the hybrid system are considered.

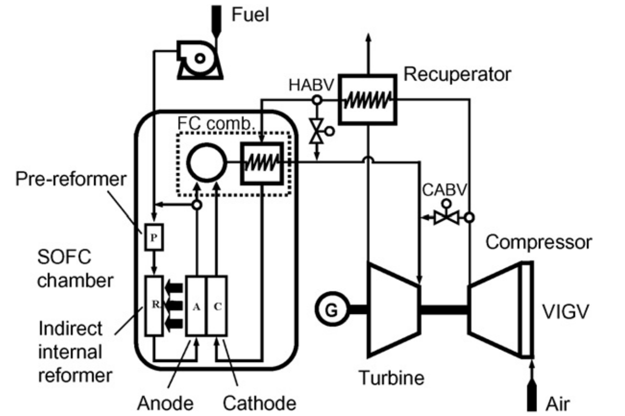

Fig. 1. Schematic diagram of the SOFC/GT hybrid system with air-bypass valves.

The configuration of the SOFC/GT hybrid system considered in this study is given in Fig. 1. This system is based on the 220-kW class Siemens–Westinghouse SOFC/GT hybrid system [1] and its specifications are given in Table 1. The SOFC and the gas turbine under the design-point conditions generated 175 and 47 kW, respectively.

Table 1
Specifications of SOFC/GT hybrid system under design-point conditions

Parameter	Value
Hybrid system	
Ambient conditions (°C, atm)	15.0, 1.0
System power (kW)	220.0
System efficiency (%)	59.3
SOFC	
SOFC power (kW)	175.0
Cell temperature (°C)	889.0
Steam-carbon ratio	2.5
Fuel utilization factor	0.85
Average current density (A m^{-2})	3200.0
Fuel inlet temperature (°C)	15.0
D.C. to A.C. conversion efficiency (%)	95.0
Gas turbine	
GT power (kW)	47.0
Pressure ratio	2.9
Turbine inlet temperature (°C)	840.0
Compressor isentropic efficiency (%)	78.0
Turbine isentropic efficiency (%)	82.0
Recuperator effectiveness (%)	89.0
Mechanical efficiency (%)	96.0
Generator efficiency (%)	95.0

Fuel (CH_4) is supplied by a fuel compressor to the SOFC chamber, which contains reformers, SOFCs, and a fuel cell (FC) combustor. The fuel is reformed by both a pre-reformer and an indirect internal reformer with the heat generated by the SOFCs and the steam recirculated from the exhaust of the SOFCs. Reformed fuel (H_2, CO) enters the anode stream of the fuel cell and reacts electrochemically with the cathode stream and produces electric power. Ambient air is pressurized by the compressor and heated by a recuperator and an FC combustor (the dotted box in Fig. 1) before entering the cathode stream of the SOFCs. The residual gases exhausted from the anode are burned in the FC combustor, which is a ducted burner for the combustion of residual gases and transfers heat to the compressed air, becoming a heat source for the turbine. The power generated by the gas turbine is the difference between the power generated by the turbine and the power required to operate the compressor. The SOFC off-gas and turbine inlet temperatures under design-point conditions are maintained at 889 and 840 °C, respectively. The turbine inlet temperature is the same as that of the FC combustor exit. Fuel entering the pre-reformer is heated to 400 °C with the help of the exhaust gas stream from the turbine.

2. Theory

The performance of an SOFC/GT hybrid system can be expressed as the power generated and efficiency, as follows:

$$\dot{W}_{\mathrm{HS}} = \dot{W}_{\mathrm{FC}} + \dot{W}_{\mathrm{GT}} \quad (1)$$

$$\eta_{\mathrm{HS}} = \frac{\dot{W}_{\mathrm{HS}}}{\dot{m}_{\mathrm{f}} \cdot LHV_{\mathrm{f}}} \quad (2)$$

where

$$\dot{W}_{\mathrm{FC}} = V_{\mathrm{c}} j A_{\mathrm{c}} \quad (3)$$

$$\dot{W}_{\mathrm{GT}} = \dot{W}_{\mathrm{turb}} - \dot{W}_{\mathrm{comp}} \quad (4)$$

The cell voltage is a function of the current density and operating temperature of the fuel cell. This is obtained from the open-circuit voltage with voltage losses such as activation and ohmic losses. Concentration losses for the range of current density considered in this study were ignored. More detailed descriptions can be found in our previous studies [5,6]. The current density is proportional to the amount of consumed fuel, as follows:

$$j = \frac{2F\dot{m}_{\mathrm{f}}U_{\mathrm{f}}}{A_{\mathrm{c}}} \quad (5)$$

Since the cell temperature depends on the amount of fuel consumed, and is influenced by the amount of air supplied to the fuel cell, the fuel cell power is a function of both fuel consumed and air supplied.

In the case of a gas turbine, the power generated is a function of air supplied, fuel supplied and turbine inlet temperature T_3, as follows:

$$\dot{W}_{\mathrm{GT}} = (\dot{m}_{\mathrm{a}} + \dot{m}_{\mathrm{f}})(h(T_3, P_3) - h(T_4, P_4)) - \dot{m}_{\mathrm{a}}(h(T_2, P_2) - h(T_1, P_1)) \quad (6)$$

Since the turbine inlet temperature is influenced by the ratio of fuel and air supplied to the gas turbine, the gas turbine power is also a function of both fuel supplied and air supplied. Therefore, the amounts of fuel and air supplied are important parameters that affect the performance of the SOFC and gas turbine, respectively, and the SOFC/GT hybrid system [6].

The power generated by the hybrid system must be reduced for part-load operation. For this purpose, the power level of either the fuel cell or the gas turbine (or both) must be adjusted according to the power required. The main goal of the part-load operation is to achieve the highest system efficiency at any power level. The reduction of fuel supplied to the system, which is called the FOC mode in this study, is the simplest control method for the part-load operation. In this case, however, two important temperatures related to the system performance, namely cell and turbine inlet temperatures, decrease rapidly due to a negligibly small change in the air supplied, and this causes a reduction in the efficiency of the system. To prevent this loss of efficiency, it is necessary to manipulate the amount of air supplied while reducing the fuel supply.

In an earlier study [5], two part-load control modes (VRS + FC and VIGV + FC) were considered for the simultaneous control of fuel and air supplied. It was found that both of these modes provide better part-load performance than that achieved with the FOC mode; however, these two modes have

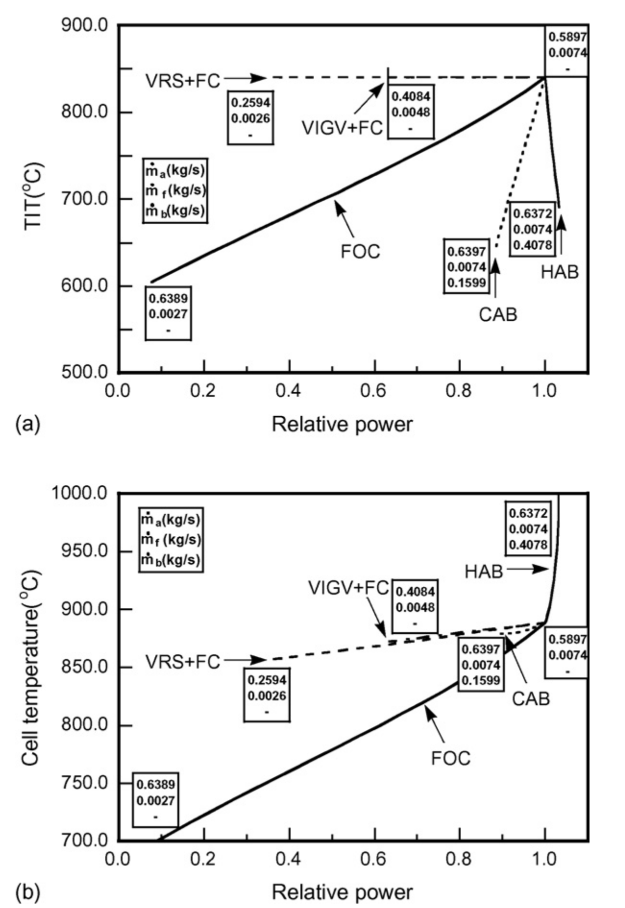

Fig. 2. Two important temperatures of SOFC/GT hybrid system with various part-load operation modes: (a) turbine inlet temperature; (b) cell temperature.

their own limitations. The VRS + FC mode is not applicable to large-class gas turbines, whereas part-load operations are possible only at a constant rotational speed, and the VIGV + FC mode limits the part-load operation range due to unstable compressor operation at the large VIGV angle.

Two air-bypass modes are considered in this study in addition to the part-load control modes of the hybrid system described in our earlier study [5], namely: (i) the CAB mode bypasses some of compressor discharge air to the turbine inlet stream and (ii) the HAB mode bypasses some air at the recuperator exit to the turbine inlet stream by manipulating air-bypass valves (CABV/HABV), as indicated in Fig. 1. Tucker et al. [7,8] used similar approaches in their experimental facility for stable start-up of an SOFC/GT hybrid system. In particular, Traverso et al. [9] applied the CAB mode to control the turbine inlet temperature in externally fired gas turbines. In this study, however, we consider the use of the air-bypass modes as an alternative for the reduction of air supplied to the fuel cell.

3. Results and discussion

For analysis of the part-load performance of an SOFC/GT hybrid system with various part-load control strategies, mathematical formulations of the thermodynamic characteristics of each component and the whole system were solved using commercial process simulation software [10]. To predict the part-load performance of the compressor and turbine of a micro gas turbine, the generalized performance characteristic maps provided by Zhang and Cai [11] and Wang et al. [12] were used. In the case of the VIGV + FC mode, the results of the performance analysis with various VIGV angles by Yang et al. [5] were adopted.

3.1. Air-bypass modes without fuel control

Fig. 2 illustrates the influence of the two air-bypass modes without fuel control (CAB and HAB) on the cell and turbine inlet temperatures, and compares them with other part-load control modes. Due to the mixing of a relatively cold air stream with the hot exhaust gas from the SOFC chamber in front of the turbine, both air-bypass modes provide a rapid decrease in the turbine inlet temperature. It is interesting to note that, unlike other modes, the power generated by the hybrid system is greater when using the HAB mode. This is caused by a rapid increase of cell temperature due to the reduction of air supplied to the SOFCs (without a corresponding adjustment of the amount of fuel supplied). The HAB mode without fuel control, therefore, cannot be used as a part-load control mode. In the case of the CAB mode, furthermore, the efficiency of the system decreases rapidly with the reduction of power (see Fig. 3) that is related to the decrease of cell temperature. The CAB mode decreases the turbine exhaust temperature, which results in a decrease of the temperature of the hot gas stream entering to the recuperator. In spite of reduced amount of air entering the recuperator under the CAB mode, the decreased temperature of hot gas stream brings a reduction in the temperature of air entering the fuel cell. It is found that the influence of low air temperature entering the fuel cell on the cell temperature is more dominant than the influence of the reduced air supplied to the fuel cell. It can be concluded that the air-bypass modes without fuel control are inappropriate for part-load control strategies.

Fig. 3 shows important features that should be considered in addition to the limitations of part-load operation of each control mode. The FOC mode, despite its lower level of system efficiency than the air/fuel control modes, provides the widest

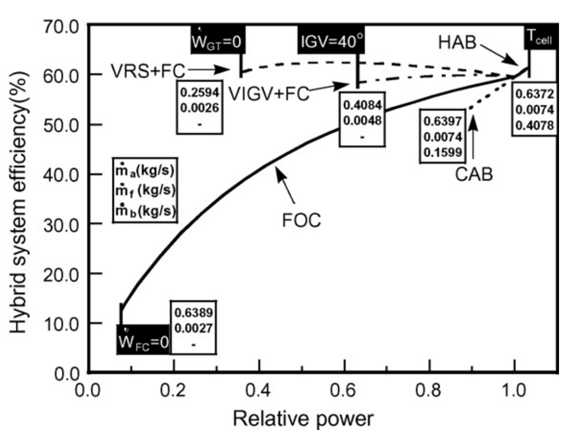

Fig. 3. Efficiency of SOFC/GT hybrid system with various part-load operation modes.

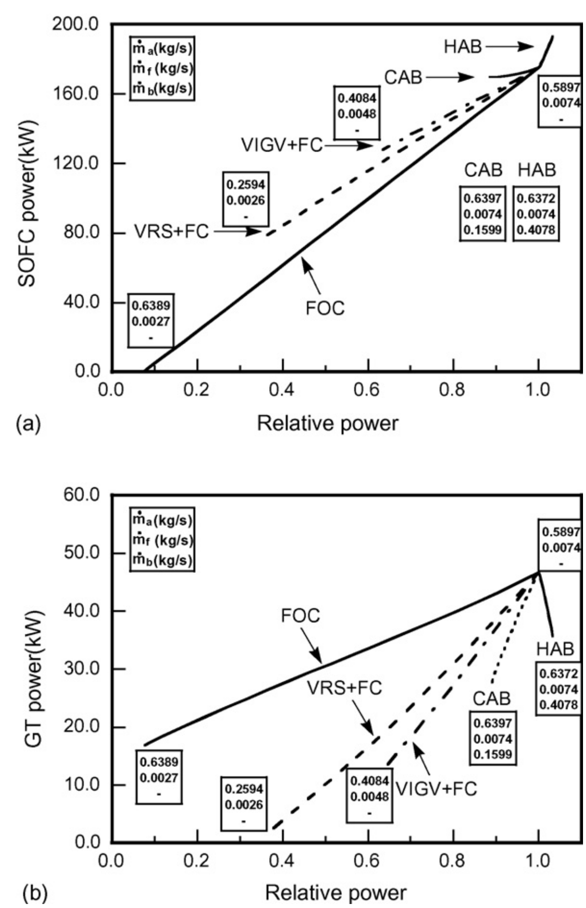

Fig. 4. Power generated by SOFC and gas turbine in SOFC/GT hybrid system with various part-load operation modes: (a) SOFC power; (b) gas turbine power.

part-load operation range. Its lowest limit of the part-load operation is due to no generation of power from the SOFC. On the other hand, the VRS + FC mode, which shows the highest level of system efficiency, cannot be operated at power levels lower than 35% of the design-point power due to zero gas turbine power. In the case of the VIGV + FC mode, the lowest limit of the part-load operation is reached due to the large VIGV angle.

The power generated by the SOFC and gas turbine with different part-load control modes is shown in Fig. 4. In the case of the FOC mode, in which only the fuel flow is manipulated, the SOFC power decreases with reduction of the fuel flow under constant fuel utilization conditions. The role of the gas turbine is dominant, which can be interpreted as the consequence of the inferior part-load performance of the FOC mode. In the case of the CAB mode, however, despite the small contribution of the gas turbine to part-load operation of the hybrid system, its level of system efficiency is lower than that of the FOC mode, as indicated in Fig. 3. This is caused by the rapid decrease of both the cell and turbine inlet temperatures caused by manipulation of a CABV position without changing the fuel flow-rate to control the load. The SOFC power in the CAB and HAB modes is influenced by the cell voltage which is a function of the cell temperature and can be changed by the amount of air supplied to the SOFC by manipulation of air-bypass valves.

3.2. Air-bypass modes with fuel control

To investigate a possible improvement of the system efficiency by air-bypass modes, these modes are coupled with the fuel control for part-load operation of the hybrid system. Fig. 5 illustrates clearly that bypassing the hot air with fuel control (HAB + FC) provides better efficiency than the FOC mode. The CAB + FC mode however, provides the worst part-load performance. Fig. 6(a) indicates that, in the HAB + FC mode, the HABV is opened to control the amount of bypassed air, maintaining a constant cell temperature from a design-point condition to around 60% of the part-load conditions. This helps to improve the part-load performance of the HAB + FC mode. On the other hand, in the case of the CAB + FC mode, it is not possible to maintain a constant cell temperature, due to the low temperature of the air entering SOFCs. The rapid drop of turbine inlet temperature in both the HAB + FC and CAB + FC modes causes no power generation of the gas turbine at about 60 and 40% part-load conditions of HAB + FC and CAB + FC modes, respectively. These are the conditions under which the power generated by the turbine is the same as that required by the compressor and, as a consequence, the gas turbine operates with no production of power (see Fig. 5(b)). After these points, the part-load operation ranges of the hybrid system with air-bypass modes can be extended to lower power levels by closing air-bypass valves

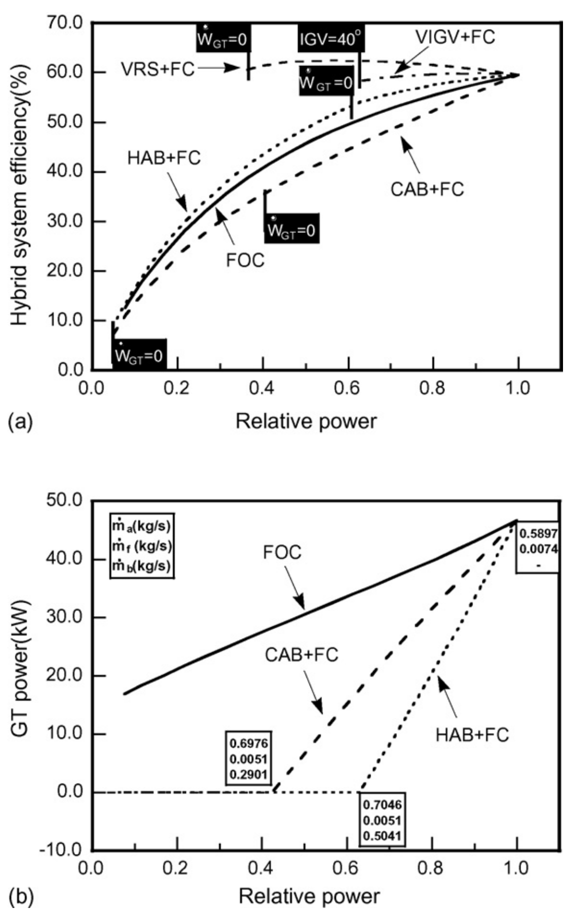

Fig. 5. Influence of air-bypass with fuel control modes on performance of SOFC/GT hybrid system: (a) hybrid system efficiency; (b) gas turbine power.

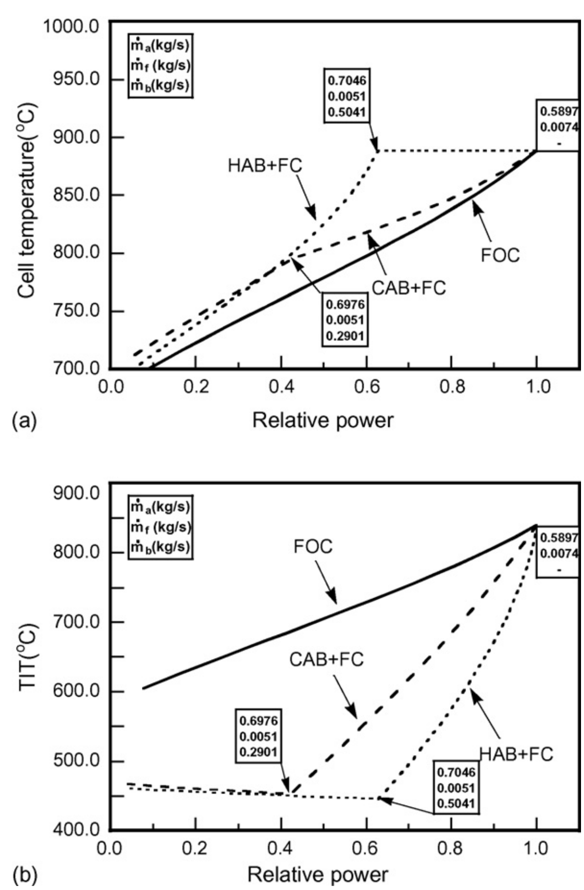

Fig. 6. Two important temperatures of SOFC/GT hybrid system operating with air-bypass with fuel control modes: (a) cell temperature; (b) turbine inlet temperature.

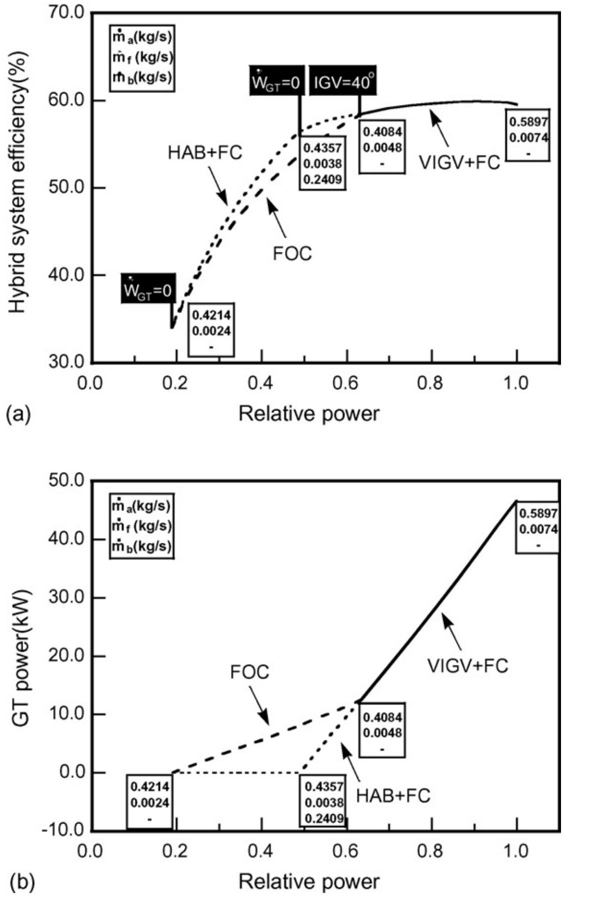

Fig. 7. Extension of part-load operation range in VIGV + FC mode of SOFC/GT hybrid system: (a) hybrid system efficiency; (b) gas turbine power.

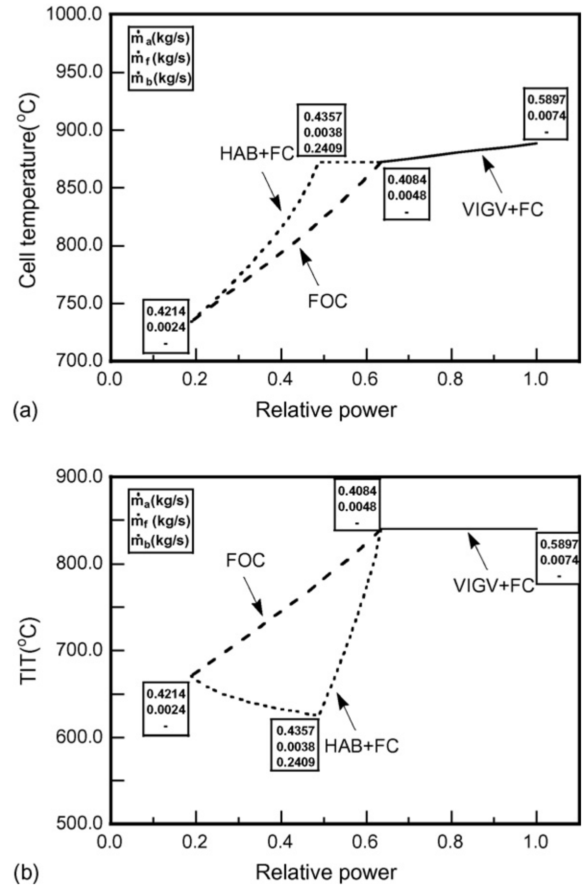

Fig. 8. Two important temperatures of SOFC/GT hybrid system operating with VIGV + FC and HAB + FC modes: (a) cell temperature; (b) turbine inlet temperature.

while maintaining the same gas turbine operation conditions, which increases the turbine inlet temperature slightly, as shown in Fig. 6(b).

3.3. Applications of air-bypass mode

As shown in Fig. 7, the air-bypass method can be applied to extend the lower limit of the part-load operation with the VIGV + FC mode. In the case of large gas turbines for power generation, the extension of the part-load operation with the VIGV + FC mode is generally achieved by applying the FOC mode after the lower limit of the VIGV + FC mode [13]. A similar concept has been applied to the SOFC/GT hybrid system, as illustrated in Fig. 7. The extension of the VIGV + FC mode for part-load operations in low power ranges is conducted by both the FOC and HAB + FC modes. The level of system efficiency of the part-load operation with the HAB + FC mode is slightly higher than in the other mode. The part-load operation range of the VIGV + FC mode is extended by opening the HABV, which increases the bypassed air from the exit air stream of the recuperator to the turbine inlet stream. This reduces the air supply to the SOFC and, therefore, it is possible to maintain the cell temperature as high as possible, as shown in Fig. 8(a). The decrease of turbine inlet temperature illustrated by Fig. 8(b), however, results in a reduction in the power generated by the gas turbine, hence approaching a condition with no power generation from the gas turbine at around 50% part-load, as described in Fig. 7(b). Extension below this point can be achieved by closing the HABV, which causes the turbine inlet temperature to increase and the cell temperature to decrease (see Fig. 8). It is found that, in this mode of operation, the part-load operation can be extended to the same range as that of the FOC mode.

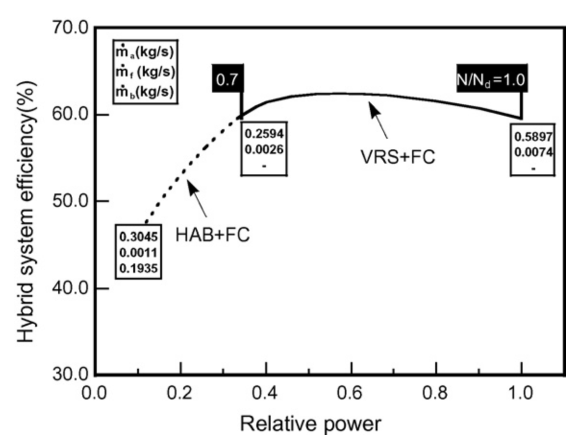

Fig. 9. Extension of part-load operation range in VRS + FC mode of SOFC/GT hybrid system.

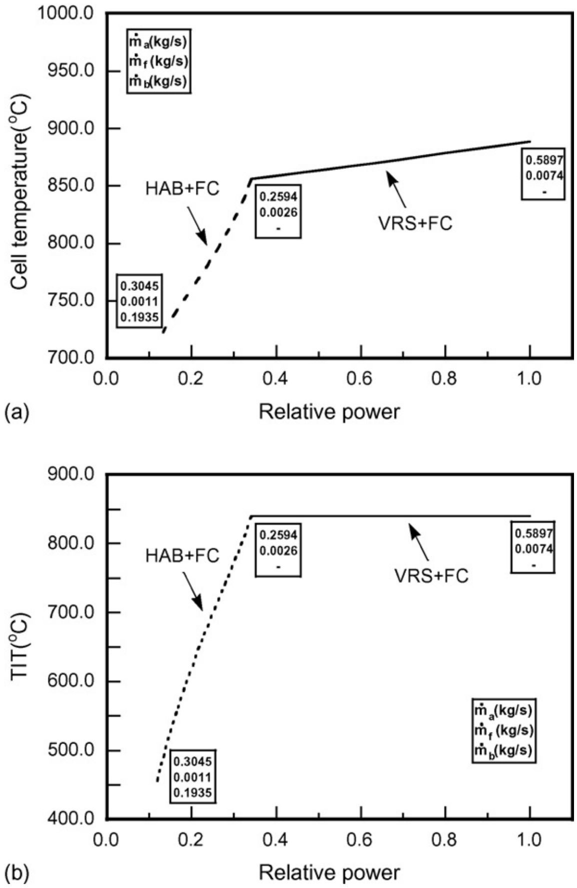

Fig. 10. Two important temperatures of SOFC/GT hybrid system operating with VRS + FC and HAB + FC modes: (a) cell temperature; (b) turbine inlet temperature.

A possible extension of the part-load operation range of the VRS + FC mode coupled with the HAB + FC mode was considered (see Fig. 9). In the case of the VRS + FC mode, the reduction in power generated with the hybrid system must be terminated at around 35% part-load conditions, which corresponds to a 70% rotational speed of the gas turbine. If the rotational speed is reduced below this level, negative power is obtained from the gas turbine. It is possible, however, to extend the part-load operation below this level by changing the VRS + FC mode to the HAB + FC mode. In spite of the decrease in both the cell and the turbine inlet temperatures in the operation range of the HAB + FC mode, as shown in Fig. 10, production of power by the gas turbine becomes positive, due to the change of the compressor performance characteristics initiated by the reduction in the turbine inlet temperature, which is related to the compatibility of the compressor and gas turbine. This is why the operation range of the hybrid system under the VRS + FC mode can be extended to lower part-load conditions by combining it with the HAB + FC mode.

4. Conclusions

To improve the part-load performance of an SOFC/GT hybrid system, control strategies using air-bypass valves have been considered in this study. Manipulation of the air-bypass valve influences the performance of both the gas turbine and the hybrid system, bypassing some of the pressurized air at the compressor exit (CAB) or at the exit of the recuperator (HAV) to the entrance stream of the turbine. From analysis of the performance, it is found that the air-bypass modes are applicable only when they are used simultaneously with fuel control. Part-load performance of the air-bypass modes with fuel control (the CAB + FC and HAV + FC modes) is less efficient than the air/fuel control modes, such as the VRS + FC and VIGV + FC, but their part-load operation ranges are larger than those of the other cases. This is made possible by extending the operation range of the gas turbine by manipulating air-bypass valves. Also, the part-load performance of the HAV + FC mode is better than that of the FOC mode over the same operating range. Finally, the HAV + FC mode can be applied to extend the part-load operation range of the VIGV + FC and VRS + FC modes by manipulating the HABV.

References

[1] S.E. Veyo, L.A. Shockling, J.T. Dederer, J.E. Gillett, W.L. Lundberg, J. Eng. Gas Turbines Power-Trans. ASME 124 (2002) 845–849.
[2] S. Campanari, J. Eng. Gas Turbines Power-Trans. ASME 122 (2000) 239–246.
[3] P. Costamagna, L. Magistri, A.F. Massardo, J. Power Sources 96 (2001) 352–368.
[4] T.W. Song, J.L. Sohn, T.S. Kim, S.T. Ro, J. Power Sources 158 (2006) 361–367.
[5] J.S. Yang, J.L. Sohn, S.T. Ro, J. Power Sources 166 (2007) 155–164.
[6] T.W. Song, J.L. Sohn, J.H. Kim, T.S. Kim, S.T. Ro, K. Suzuki, J. Power Sources 142 (2005) 30–42.
[7] D. Tucker, L.O. Lawson, R.S. Gemmen, ASME Paper GT2005-68784, 2005.
[8] D. Tucker, L.O. Lawson, J. VanOsdol, J. Kislear, A. Akinbobuyi, ASME Paper GT2006-91291, 2006.
[9] A. Traverso, R. Scarpellini, A.F. Massardo, ASME Paper GT2005-68100, 2005.
[10] Aspen Plus™, Aspen Technology Inc., 2004.
[11] N. Zhang, R. Cai, Energ. Convers. Manage. 43 (2002) 1323–1337.
[12] W. Wang, R. Cai, N. Zhang, Appl. Therm. Eng. 24 (2004) 1851–1863.
[13] J.H. Kim, Analysis on transient behavior of gas turbines for power generation, Ph.D. dissertation, Seoul National University, 2000.